UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
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OFFICE OF CHEMICAL SAFETY
AND POLLUTION PREVENTION

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MEMORANDUM

SUBJECT: Overview of Application Methods and Factors, Use, Usage, and Benefits of Commodity and Structural Fumigants: Phosphine [(066500) including Aluminum Phosphide (066501) and Magnesium Phosphide (066504)], Propylene Oxide (042501), Sulfur Dioxide (077601), Sodium Metabisulfite (111409), Sulfuryl Fluoride, (078003), Ethylene Oxide (042301), and Methyl Bromide (053201)

FROM: R. Murphey Coy, Ph.D., Entomologist
Bill Chism, Ph.D., Senior Biologist
Biological Analysis Branch
Biological and Economic Analysis Division (BEAD) (7503P)

Whitney Hodde, M.S., Economist
Economic Analysis Branch
Biological and Economic Analysis Division (BEAD) (7503P)

Lindsey Hendrick, Biologist
Briana Otte, Biologist
Science Information and Analysis Branch
Biological and Economic Analysis Division (BEAD) (7503P)

THRU: Monisha Kaul, Chief
Biological Analysis Branch
Biological and Economic Analysis Division (BEAD) (7503P)

Timothy Kiely, Chief
Economic Analysis Branch
Biological and Economic Analysis Division (BEAD) (7503P)

Hope Johnson, Chief
Science Information and Analysis Branch
Biological and Economic Analysis Division (BEAD) (7503P)

TO: Jonathan Williams, Chemical Review Manager, RMIB II
Matthew Khan, Chemical Review Manager, RMIB I

Sue Bartow, Chemical Review Manager, RMIB IV
Tiffany Green, Chemical Review Manager, RMIB II
Jocelyn Hospital, Team Leader, RMIB II
Matthew Manupella, Acting Team Leader, RMIB I
Nicole Zinn, Team Leader, RMIB II
Julie Javier, Team Leader, RMIB IV
Pesticide Re-evaluation Division (PRD) (7508P)

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SUMMARY

Fumigants used on commodities and structures storing commodities are beneficial because they control economically important pests, including those which are critical to control to ensure food is safe for human consumption as well as pests whose damage may result in the adulteration or spoilage of food and non-food commodities. Further, fumigants provide benefits to users as they can be used to control pests that directly attack or infest structures (e.g., termites, bed bugs). This document summarizes the key benefits of commodity and structural (or space) fumigants and provides information on how these fumigants are deployed in order to inform viable risk mitigation proposals for these types of fumigants.

Fumigants are chemicals which, at a required temperature and pressure, can exist in a gaseous state and are lethal to target organisms when present in sufficient concentrations. The advantages of fumigants include: 1) pest control options that are fast acting and/or broad-spectrum that may result in pest eradication, 2) the ability to penetrate and treat commodities and structures that cannot be easily reached with other pesticides while leaving minimal or no surface residues, and 3) the combined suite of commodity and space fumigants offer multiple methods of application, and this in turn allows fumigants to be applied to many different pests and use sites. Fumigants are also important in preventing the movement of pests from one location to another which facilitates safe international trade and protects U.S. agriculture and natural resources from the entry, establishment and spread of an economically or environmentally significant pests.

The use of a fumigant is generally considered the last option in an integrated pest management (IPM) plan to control pests (e.g., insects, microbes and pathogens, mold, rodents) in commodities and structures when other control options have failed or are infeasible. As fumigants are often the last option for pest control, few alternative sterilization technologies are available for pest control in commodities and structures. In some cases, commodities or structures may be treated with a non-fumigant alternative which include heat, steam or irradiation treatments. However, not all commodities (e.g., nuts, herbs and spices) and structures are compatible with heat or steam sterilization. For example, the exposure of nuts, herbs, and spices to heat and moisture (steam) may not sufficiently reduce pathogen loads to the necessary levels to meet FDA food safety requirements can negatively impact the quality of the commodity (e.g., mouthfeel, texture, aromatics, clumping of spices). Further, irradiation sterilization methods do not have market

acceptance in the U.S. For structures and spaces, the main alternatives include insecticides as well as prevention and sanitation practices.

The benefit of each commodity and structural fumigant is underscored by the fact that any one fumigant cannot be easily substituted for another and, therefore, each fumigant is not considered a direct alternative to another. This is because individual fumigants are often specialized for a specific pest spectrum (e.g., insects or microbes) and/or pest life stage (e.g., insect eggs or larvae). Moreover, the chemical characteristics (e.g., flammability, corrosiveness) of individual fumigants may require different approaches to be both safely deployed and still be effective on the target pest (UKPSEP, 2016). For example, phosphine and metal phosphides cannot be used in vault fumigations that utilize vacuum conditions due to the potential for fire/explosions, whereas Ethylene oxide (EtO) can only be used in vacuum fumigations or gas-tight chambers, which reduces the potential for fire/explosions resulting from exposure to atmospheric oxygen while increasing fumigant penetration.

The Agency is currently reviewing the registrations of these fumigants, and this document provides a breakdown of the most common use sites, primary target pests and usage data for each fumigant, as well as summary information about the facility types, application methods and formulations used which can be helpful for understanding how these fumigants are similar or different from one another.

The fumigants covered in this document along with the key benefits of each are summarized here:

- Phosphine and metal phosphides (aluminum and magnesium phosphide) offer broad-spectrum pest control of insects (all life stages) and rodents. Phosphine is widely used for the protection of grains and other commodities and can be used to fumigate in-transit commodities in railcars and ship holds.
- Propylene oxide (PPO) is used on a wide variety of commodities to control insect pests and microbes to ensure food safety for human consumption. PPO can control *Salmonella,* aflatoxins, or other pathogens on raw nuts as well as herbs and spices.
- Inorganic sulfites (sulfur dioxide, sodium metabisulfite) are critical for the protection of grapes from gray mold. Without the control of gray mold on grapes in storage or transport, complete loss may occur as the grapes quickly rot and become unmarketable.
- Sulfuryl fluoride is highly important for the control of pests such as drywood termites, wood boring insects, bed bugs, and cockroaches in structures and buildings. Sulfuryl fluoride is also valuable for protecting commodities such as grain and may be used against phosphine resistant pests.
- EtO is important for ensuring food safety from the control of pathogens such as *Salmonella* and *Escherichia coli* on herbs and spices. It is also commonly used in medical device sterilization.
- Methyl bromide is effective against many pests in a wide variety of commodities, requires a short exposure period for efficacy, and easily diffuses and rapidly penetrates the pore spaces of commodities. Although the majority of uses have been phased out, methyl bromide remains highly coveted for trade purposes. Its fast-acting and highly

efficacious characteristics make it ideal at port and inspection sites where treatments are time sensitive and international phytosanitary standards require that certain pests be killed at very high rates.

A different risk mitigation approach may be required for each individual fumigant. Risk mitigations will be determined by the evaluated risk picture and the practicality and economic viability of the mitigation approach that is being considered; therefore, proposed mitigations considered by the Agency will be more thoroughly assessed in the individual Proposed Interim Decision (PID) for each fumigant. For example, capture systems are often raised as a potential way to mitigate bystander exposure risk or environmental damages of a fumigant. Feasibility and cost are relevant factors if EPA were to consider imposing any requirements for capture systems. Therefore, included in this memo is a summary of the information BEAD was able to collect related to the status of capture system adoption by fumigant and the costs of capture systems.

Without effective fumigants users might have to shut down a facility and use micro-sanitation to clean and sanitize the structure, destroy contaminated product, or sell it at a substantially reduced price. Destroying contaminated product can be exorbitantly expensive.

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BACKGROUND

The Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) Section 3(g) mandates that the Environmental Protection Agency (EPA or Agency) periodically review the registrations of all pesticides to ensure that they do not pose unreasonable adverse effects to human health and the environment. This periodic review is necessary in light of scientific advancements, changes in policy, and changes in use patterns that may alter the conditions underpinning previous registration decisions. In determining whether effects are unreasonable, FIFRA requires that the Agency consider the risks and benefits of any use of the pesticide.

The Agency has completed draft risk assessments for methyl bromide, sulfuryl fluoride, and inorganic sulfites (sulfur dioxide and sodium metabisulfite), propylene oxide, phosphine, aluminum phosphide, and magnesium phosphide. Draft risk assessments for sulfuryl fluoride and EtO are currently in development and are expected to publish on a later date.

PURPOSE AND METHODOLOGY

This document serves two purposes: to summarize the benefits of commodity and structural fumigants, and to provide information to support viable risk mitigation proposals for individual commodity and structural fumigants. Fumigants are often used in enclosed spaces (and are highly mobile). Therefore, it is important to know how fumigants are used and in what structures fumigations are performed to understand potential risks posed to workers and bystanders as well as potential implications for air quality. Managing such risks requires managing the storage, application, escape, release and disposal of these fumigants.

Risk mitigation options for individual fumigants are likely to vary due to the differences in use patterns and risks. The impacts of proposed risk mitigations considered by the Agency will be assessed in the Proposed Interim Decision (PID) for each fumigant. BEAD has included all commodity and structural fumigants in one document because each fumigant offers different characteristics that makes it uniquely valuable to specific use sites and patterns. While there is some overlap in how these fumigants are or can be used, it is helpful to see how each fumigant relates to, or is different from, another. Not any one fumigant offers a quick one to one replacement of another, each has its advantages and drawbacks. For example, methyl bromide is an ozone depleting substance that has been phased out except for quarantine and pre-shipment or critical use exemptions which are subject to EPA approval. Phosphine can be used as replacement to methyl bromide for some use sites and offers a lot of benefits but has drawbacks in that it is corrosive to metals, requires a longer time period to complete fumigation and has resistance issues.

OVERVIEW OF COMMODITY AND STRUCTURAL FUMIGANTS

Fumigants aid in the production and protection of the food supply chain and commodities whether applied to soil as part of crop production (see Chism and Sells, 2019) or to commodities or spaces post-harvest (Walter, 2006). It has been estimated that globally 25% of harvested crops are destroyed during storage and transport by insects, microbes, and vertebrate pests (Pimentel, 2007). USDA's Crop Protection and Quarantine Program notes the impact insects have on the quality of stored grain and other stored products, reporting that postharvest losses to corn and wheat can amount to as much as $2.5 billion annually (USDA ARS, 2019). No matter how many preventative and monitoring measures are employed, commodities and spaces are susceptible to pest pressure, both because the product itself can attract pests for feeding but also because very nature of bulk storage units (warm and dark conditions) can attract pests.

Fumigants are defined as chemicals which, at a required temperature and pressure, can exist in a gaseous state and are lethal to target organisms when present in sufficient concentrations (Bond, 1989; Mueller, 1998). As fumigants function as gases, they are distinguished from pesticides that are applied as fogs, mists, or smokes, which are suspended solids or liquids (Mueller, 1998; Walter, 2006). Individual fumigants are typically more effective against a specific target pest spectrum (i.e., insects or pathogens) relative to one another. For example, phosphine and the metal phosphides are commonly used to target insects whereas inorganic sulfites (i.e., sulfur dioxide, sodium metabisulfite) target fungi. The use of fumigants for controlling pests in commodities or structures is often considered the last option for pest control in an integrated pest management (IPM) program. As such, fumigants are recommended to be used when other pest control measures have failed or are impractical. However, the use of fumigants may be standard operating procedures in certain scenarios such as when commodities are fumigated for quarantine purposes required for trade or when used for public health purposes. Broadly, the advantages of fumigants include: fast acting and/or broad-spectrum control that may result in pest eradication; the ability to penetrate and treat commodities and structures that cannot be easily reached or that are impractical with other pesticides; minimal or no surface residues; and, because different fumigants offer different advantages, the full suite of fumigants provide pest managers with multiple potential methods for application to many different pests and use sites (Hopkins and Johnson, 2013).

Fumigants are formulated and stored as solids, liquids, or gases. Solid and liquid formulations release gases after exposure to certain environmental conditions (i.e., atmospheric moisture, water, heat). Following release, gases diffuse and penetrate commodities, structures, cracks and crevices to disinfest commodities and/or spaces (Leesch et al., 1995). While fumigants can quickly disinfest a commodity or structure from pests (i.e., insects, pathogen, mold), they are only effective against pests while the gas is present and do not provide residual pest control (Leesch et al., 1995). The selection of a fumigant is influenced by considerations such as the commodity or structure to be fumigated, target pest(s) and life stage, fumigant's chemical characteristics, and fumigation method to be used. Therefore, before a fumigation takes place, fumigators should identify the target pest(s) to be controlled to ensure the proper fumigant and setting are selected.

Common Types of Commodity and Structural Fumigations

Commodity fumigation refers to fumigation treatments that eliminate pests such as beetles (e.g., rice weevil, granary weevil, red flour beetle), moths (e.g., Indianmeal moth), cockroaches, mites (e.g., *Tyrophagus putrescentiae* or ham mite), microbes and pathogens (e.g., *Salmonella*, *Escherichia coli, Botrytis* spp., aflatoxins,), mold, and/or rodents in a commodity such as cheese, dried meat, fruits, grains, herbs, spices, or wood. The commodity may be stored in sealed or enclosed containers such as grain silos, chambers, shipping containers, or packaging.

Structural or space fumigation is a pest control method that relies on filling the airspace of a sealed or enclosed structure with a toxic gas. Structural fumigation treatments eliminate pests that can infest/attack the structure or items within the structure such as bed bugs, cockroaches, termites, wood boring insects, birds, rodents, and other stored product pests in enclosed spaces such as airplanes, cars, ship holds, wheeled carriers (boxcars and truck trailers), buildings, homes, mills, and warehouses.

The most common fumigation methods for commodities and structures include vault, tarpaulin, and spot (local) fumigations (Hopkins and Johnson, 2013).

Vault Fumigations

Vault fumigations of commodities are typically conducted in atmospheric chambers or vacuum chambers (also referred to as commercial sterilization chambers). Commodities and other structures such as buildings/warehouses, truck trailers, boxcars/railcars, or grain bins/silos may be used as vaults, if properly taped and sealed (Hopkins and Johnson, 2013).

Atmospheric chambers are used to conduct fumigations in airtight structures under atmospheric or normal air pressure. The chambers are small, isolated buildings or structures that have a constant volume. Atmospheric chambers are not recommended to be within or connected to other structures where fumigant passage may occur (Hopkins and Johnson, 2013). Atmospheric chambers require minimal equipment to deliver, circulate, and remove gas in addition to minimal equipment to heat the chamber (Hopkins and Johnson, 2013). Gas detection equipment (discussed below), which is used to monitor fumigant concentration levels can be permanently installed in atmospheric chambers.

Vacuum chambers are large, steel structures. Air pressure (oxygen) is reduced or removed during a vacuum fumigation. The reduction in air pressure allows for greater gas penetration into the commodity and stresses the respiration of pests such as insects, which may reduce the fumigation time relative to atmospheric chamber fumigations. Restored pressure and sustained-vacuum fumigations are the two main methods used to conduct vacuum fumigations (Hopkins and Johnson, 2013).

A restored pressure vacuum lowers the chamber's pressure, introduces the fumigant and then restores pressure in one of four ways. Pressure is either restored using gradual, delayed, immediate, or simultaneous methods (Hopkins and Johnson, 2013). Gradual restoration is generally considered the most effective method. Gradual restoration releases the fumigant and then re-introduces air over a two to three-hour period. Delayed restoration releases the fumigants and then holds the chamber under vacuum conditions for 45 minutes before rapidly reintroducing air to the chamber. Immediate restoration releases the fumigant and then rapidly introduces air to the chamber. Lastly, simultaneous introduction uses metering equipment to release a mixture of air and fumigant into the chamber.

A sustained-vacuum fumigation reduces the pressure within the chamber while introducing the fumigant, creating a partial vacuum. The manner in which air pressure is returned to the chamber from a sustained-vacuum fumigation is somewhere between delayed and immediate restoration methods (Hopkins and Johnson, 2013).

A tape and seal structure (e.g., building, silo, boxcar) fumigation relies on creating a temporary fumigation chamber that is airtight or as close to airtight as possible. To accomplish this, workers inspect the building and roof to cover doors, windows, vents, chimneys, drains, open pipes as well as structural flaws (cracks, holes, other openings) with plastics, caulking, tape or other adhesives (Hopkins and Johnson, 2013). During this process all air moving systems (e.g., air conditioning, supply air) that could negatively impact the fumigation within the structure are turned off. Structures that are more tightly sealed will result in more efficient fumigations. Certain building materials such as wood or cement blocks are more porous and do not hold gases for as long as structures built with metal, cement, or plastics (Hopkins and Johnson, 2013).

Tarpaulin Fumigations

Tarpaulin (tarped) fumigations can be used to treat commodities as well as entire structures in both indoor and outdoor settings (Hopkins and Johnson, 2013; UKPSEP, 2016). A tarpaulin fumigation places a semipermeable tarp over the commodity or entire structure and then ground sealed to create an air-tight enclosure. The fumigant is then released and circulated under the tarp until the pest(s) are controlled. Tarpaulin fumigations are commonly used to remove pests, termites and wood-boring insects (e.g., beetles) from structures (Hopkins and Johnson, 2013; UKPSEP, 2016). An advantage of tarpaulin fumigations for commodities is that it provides fumigators an option to treat only infested materials instead of having to move materials into treatment chambers or treat an entire warehouse or building (Hopkins and Johnson, 2013; UKPSEP, 2016). This targeted approach can save time and money.

Spot (Local) Fumigations

A spot or local fumigation is a short-term treatment of machinery/equipment and small areas/storages within mills, food and feed processing plants, breweries, and other similar industries that are susceptible to buildup of non-moving stock and pests (Hopkins and Johnson, 2013). Machinery or areas to be fumigated should be isolated or sealed off. Machinery or equipment may also have fumiports. Fumiports are openings that can be used to introduce and recover fumigants such as prepackaged phosphine products, which leave behind a dust or solid residues (Hopkins and Johnson, 2013). Spot fumigations frequently target insect pests that infest whole foods and food particles that remain within processing equipment and may need to be repeated due to the susceptibility of different life stages (eggs, nymphs and larvae, pupae, and adults) to various fumigants (Hopkins and Johnson, 2013). Equipment that is commonly disinfested with spot fumigations include elevator boots and heads; sifters, rollers, and dusters; conveyers, filters, purifiers, and spouting.

Factors Impacting Fumigation Efficacy

Key factors that can impact the efficacy of the fumigation process include temperature and moisture (humidity), gas movement (penetration) and sealing, and fumigant concentration (dose) and holding time (Hopkins and Johnson, 2013; UKPSEP, 2016). A fumigator must consider these to ensure pest populations are effectively killed in commodities and spaces. Practically speaking, fumigation is a function of gas concentration and exposure time. This section reviews factors impacting the efficacy of fumigation.

Temperature and Moisture (Humidity)

It is important for any pest manager or fumigator to consider the temperature and moisture levels (humidity) when performing a fumigation. Commodities and structures may be heated/cooled or adjust humidity levels to desired levels prior to fumigation (Walter, 2006). For many fumigants to be fully effective it is preferred that fumigations be performed during warmer months or are when ambient air temperatures are between 60 to 80° F (UKPSEP, 2016). Fumigations performed at colder temperatures (below 40° F) are less effective than fumigations at higher temperatures, especially against insect pests (Walter, 2006). At lower temperatures, surfaces such as walls sorb more gas which may impact the amount of gas reaching the commodity. Additionally, gas molecules do not move as rapidly through cold air as in warmer air, resulting in poor gas penetration into commodities and spaces (Walter, 2006). Further, insect activity and respiration are decreased at lower temperatures and so the fumigation exposure time may be insufficient to achieve control (Walter, 2006).

Moisture impacts fumigant penetration into commodities and spaces. In some cases, commodities and structures that have a high moisture content will require a higher fumigant dose due to increased sorption of moisture by the commodity and decreased fumigant penetration into the commodity (Hopkins and Johnson, 2013; UKPSEP, 2016). In other cases, if the air is too dry or the moisture content of the commodity is too low, then “moisture-activated” fumigants (e.g., metal phosphides) will not fully release and pests may not be adequately controlled (UKPSEP, 2016). A further consideration when dealing with phosphine is that it is corrosive to certain metals (i.e., brass, copper) and can damage electrical and mechanical systems when exposed to excessive moisture/humidity (Walter, 1991; Walter, 2006).

Gas Movement (Penetration) and Sealing

When introduced into a commodity or space, gases move from areas of higher concentrations to areas of lower concentrations. For fumigations to be successful, an even distribution or equilibrium of the gas at the required concentration is necessary (Walter, 2006). Fumigators can monitor and record gas concentrations before, during, and after a fumigation with several types of devices (discussed below). To ensure proper gas movement, fumigators rely on fans to move gases throughout a commodity or space and the fans also help with aeration at the end of the fumigation process. Additionally, some fumigants used in grain silos or ship holds such as phosphine are more effective when used with air recirculation practices or closed loop fumigation (CLF) systems which aide in moving the gas from the top (headspace) to the bottom or base of the commodity or space. Once the proper gas concentration is achieved throughout the commodity or space, the fumigation process begins (Walter, 2006). During the fumigation process, gases can also penetrate cracks and crevices as well as certain packaging materials to control pests that may otherwise be difficult or impractical to control with other control options (UKPSEP, 2016). At the conclusion of the fumigation, fans and aeration blowers or CLF systems can be used to vent and purge the gas (Noyes et al., 1995a). Proper sealing is often considered the most important step to ensure the efficacy of a fumigation (UKPSEP, 2016). Gases introduced to commodities and spaces are subject to possible loss from leakage or sorption (Walter, 2006). Losses from sorption and leakage increase the amount of gas required and thus the cost of fumigation. To minimize losses from sorption in colder weather, fumigators may heat a space prior to fumigating. To prevent losses from leakage, fumigators will ensure commodities and spaces are properly sealed. If not properly sealed, it is likely that the necessary concentration of gas will not be maintained throughout the fumigation process for an efficacious application. Fumigators commonly use tarping, plastics, tape, adhesive sprays, and other sealants to ensure that commodities and spaces are properly sealed to minimize losses from fumigant leakage.

Concentration (Dose) and Holding Time

The concentration or fumigant dosage is the total quantity of a gas introduced into a commodity or space. The concentration of gas needed is related to the volume (cubic feet) being fumigated. The holding time is the length of time required for the commodity or space to be exposed to the fumigant for effective pest control, which varies by fumigant and/or commodity. With some fumigants, such as methyl bromide, sulfur dioxide, or sulfuryl fluoride, applicators can use more or less gas for the space or commodity which can decrease or increase the exposure time required to complete the fumigation. The exposure time necessary for other fumigants such as phosphine or metal phosphides cannot be decreased with the addition of more phosphine (Walter, 2006; Hopkins and Johnson, 2013). As phosphine gas is released/liberated slowly, a longer exposure period (at least 48 hours) is necessary to allow for gas buildup overtime before the fumigation begins (Hopkins and Johnson, 2013).

As previously mentioned, fumigators can detect or monitor the concentration of a gas with several devices (Walter, 2006; Hopkins and Johnson, 2013; UKPSEP, 2016). These devices may be handheld or used remotely. Gas detection devices include halide gas detectors, thermal conductivity analyzers, glass detector tubes, ambient air analyzers or infrared detectors, gas analyzers, as well as photoionization, flame ionization, and electron capture devices. Not all devices are compatible with each fumigant. These devices allow fumigators to monitor gas concentrations over time. Monitoring gas concentrations can ensure worker or bystander safety prior to, during, or post-fumigation as well as provide real-time air monitoring levels to ensure aerated gases are being in released in accordance with air quality and label restrictions.

Halide gas detectors can detect five nonmetallic halogen elements: fluorine, chlorine, bromine, iodine, and astatine when concentrations are at or above 50 parts per million (Hopkins and Johnson, 2013). Gas detection with a halide detector relies on exposure of an air sample to an open flame. The color and intensity of the flame indicate the gas present and its estimated concentration. Halide gas detectors cannot be used with flammable or explosive gases or in mills, grain elevators, or other enclosures that may contain grain dust that may explode. Halide gas detectors are not used to determine whether fumigant levels are safe for re-entry.

Thermal conductivity analyzers may be portable devices that measure the concentration of gases within chambers or other enclosures during fumigation (Hopkins and Johnson, 2013). Thermal conductivity analyzers detect multiple gases and work by having electrical currents pass through a wire exposed to air samples. The temperature of the wire indicates the concentration of gases, with higher wire temperatures indicative of higher gas concentrations. As the devices may be sensitive to multiple gases, sorbing materials such as sodium hydrate may be added to the sampling line that runs through the fumigated area to obtain true readings of the fumigant being used. The devices cannot measure gas concentrations below five parts per million and are not appropriate for determining gas levels for re-entry.

Glass detector tubes or color diffusion detector tubes are disposable glass tubes that are fumigant specific (Walter, 2006; Hopkins and Johnson, 2013; UKPSEP, 2016). These devices draw air through the tube and a color reaction indicates the gas concentration. Glass detector tubes can detect both high-ranges and low-ranges of gases. High-range tubes are recommended for use during the fumigation and low-range tubes are used to determine if an area is safe for re-entry.

Ambient air analyzers or infrared detectors are spectrophotometers that detect and measure gas concentrations by measuring the wavelength absorption of infrared radiation following gas exposure (Hopkins and Johnson, 2013). Devices may be portable and can be calibrated to detect both high (0 to 150 parts per million) and low-range (0 to 15 parts per million) gas concentrations for specific fumigants. High-range detection can be used to detect leaks during the fumigation whereas low-range detection can be used for determining safe concentrations for re-entry.

Gas analyzers are used to detect leaks during the fumigation process as well as the gas concentration before re-entry (Hopkins and Johnson, 2013). Gas analyzers are commonly lightweight, portable devices that are designed for the detection of a particular fumigant or gas. Gas analyzers detect gas concentrations by drawing air samples through a tiny furnace with a pump.

Additionally, more sophisticated detectors that may provide more sensitive or different readings than the previously mentioned devices are available to fumigators (Hopkins and Johnson, 2013). These devices may be able to detect gas concentrations ranging from sub part per billion and 10,000 parts per million and include photoionization, flame ionization, and electron capture devices.

Aeration, Release and/or Capture

Aeration is required at the end of every fumigation and is the process of replacing or diluting fumigant-containing air with fresh air that contains little or no fumigant. Aerated gases are either released into the environment or recaptured and destroyed. The aeration process may also be referred to as 'air-washing' in vacuum fumigations. The aeration process may differ by fumigant and the item or space that is fumigated as well as the location (indoors or outdoors) of the fumigation. For example, fumigant chambers within structures are likely to have intake pipes that bring in fresh air and exhaust pipes that release fumigant-treated air into the environment and/or fumigant capture systems. The rate of aeration and release and/or capture increases as the rate of airflow increases within the intake and exhaust pipes. Buildings and fumigant chambers that are located outside may require the opening of doors and/or windows and turning on ventilators and fans for aeration and release. Depending on the fumigant used or proximity to other structures, grain bins and silos may require air recirculating or CLF systems whereas the use of some fumigants and/or locations would only require air vents and doors be opened for aeration and release. Tarpaulin fumigations can be aerated and released by placing a blower at one end and lifting the tarp at the other end.

Regardless of what is being aerated, the aeration period must be long enough to allow the gas to desorb (release) from the commodity or space. Factors that impact the time required for aeration include rate of air exchange, air temperature, and sorption and desorption rates of the fumigant. The rate of air exchange is the most critical factor for aeration times. Generally, it is recommended that the use of fans or other aeration equipment that are capable of moving the volume of air per minute or one 'air change' per minute be used in atmospheric chambers and other enclosures (USDA-APHIS-PPQ, 2016; Hopkins and Johnson, 2013). Temperature affects the aeration process in a similar manner as the fumigation process. The rate of aeration is increased at higher temperatures. In colder weather, fumigators may also heat the space to increase the temperature and desorption rate. For most fumigants, the optimal aeration temperature is reported to be 76° F, which corresponds to the optimum fumigation temperature range of 60 to 80° F (Hopkins and Johnson, 2013; UKPSEP, 2016). Specific fumigants vary in their sorptive properties. The desorption rate of gases from commodities or spaces is also decreased at colder temperatures and requires more time to diffuse. The surface area of the commodity or structure also impacts the desorption rate. Commodities such as wheat and other grains have large surface areas relative to loosely packed materials and require more time to complete the aeration process.

Capture Systems

Capture systems can reduce the risk of bystander exposure due to fumigant leakage and reduce the amount of toxic gas emissions released during or after a fumigation treatment. BEAD gathered information on which fumigants are captured and how they are captured as well as information on the cost of some of these systems. Feasibility and cost are relevant factors if EPA were to consider imposing any requirements for capture systems. Therefore, BEAD reports the following collective findings of USDA Office of Pest Management Programs (USDA OPMP,

2020) outreach, information provided by current registrants and any other publicly available information on fumigant capture. The following is a summary of the findings by fumigant:

- Ethylene Oxide (EtO) – Spice treatment facilities in the U.S. are subject to the provisions of the Clean Air Act National Emissions Standards for Hazardous Air Pollutants (NESHAP) for ethylene oxide. NESHAP requires greater than 99% control of the emissions from the sterilizer vent, the primary source of emissions. According to a representative of the spice industry (personal communication, E. Ruckert with USDA OPMP, 2020) all EtO facilities in the U.S. are equipped with capture technology and some facilities use multiple devices to capture and control emissions.

  USDA OPMP (2020) collected information from several spice equipment manufacturers. The manufacturers reported that EtO can be captured and destroyed by wet scrubbers which convert ethylene oxide and water into ethylene glycol (USDA OPMP, 2020). To accomplish this, the recapture systems use: bubblers, packed towers, hybrids of these two, catalytic oxidation or dry bed absorption (USDA OPMP 2020).

  According to information submitted to USDA OPMP by spice equipment manufacturers, the initial cost of EtO capture and control devices can range from $100,000 to $2,000,000 depending on facility size (cost does not include installation, integration and continuous monitoring). Operating costs also range widely depending on both the size of the facility and the ambient weather conditions because the technology heats air from ambient temperature to above 280° F. Therefore, operating costs are more expensive in cooler climates.

- Inorganic Sulfites: sulfur dioxide and sodium metabisulfite – Current labeling restricts the concentration of sulfur dioxide that can be released for a treatment scenario. Use information of sulfur dioxide is detailed in MRID 50188501 (Kay, 2017) and details on the sulfur dioxide fumigation process is summarized in the human health draft risk assessment (Drew et al., 2020) As reported in the draft risk assessment, most cold storage facilities utilize a wet scrubbing process, whereby efficient refrigeration systems are designed to pass refrigerated air through a water spray, lowering the sulfur dioxide concentration in the room below 2.0 ppm (per label requirements) upon completion of the fumigation process. No information was reported on the cost of establishing or operating this scrubber technology.

- Phosphine and metal phosphides – Most of phosphine in the U.S. is vented and aerated because phosphine is most used on grain bins. Capture technology (scrubbers) is also available but BEAD does not have information on adoption rates in the U.S. No information was reported on the cost of establishing or operating a phosphine capture system.

- Sulfuryl Fluoride– Based on professional judgement BEAD expects that sulfuryl fluoride is aerated when used to fumigant buildings and structures (not a use site that would be eligible for capture) and that capture systems would be more likely to be used when treating commodities like fruits and nuts. Information available to BEAD from Nordiko International indicate that recapture systems for sulfuryl fluoride are under development. Another source, Swords (2011) reports that a system is already available but did not provide a complete description of how the system works. BEAD does not know how widely adopted these systems are and does not have information on their associated costs.

- Propylene Oxide (PPO) – The PPO label requires that scrubbers operate at a 95% efficiency. According to the registrant many facilities operate at a higher efficiency than 95% (EPA, 2020a). Except for a couple of small facilities, all facilities using PPO currently use scrubbers (EPA, 2020a). The scrubbing process is similar to that used in EtO. In this case, propylene oxide reacts with water to form propylene glycol. Because this is a slow process an acid catalyst may be added to speed the process (Verantis, 2020). No information was reported on the cost of establishing or operating a PPO capture system.

- Methyl bromide – Currently available capture systems are either carbon based where methyl bromide is trapped and held by adsorption to activated carbon or solution or heat based (Swords, 2011). In the solution-based system, methyl bromide is agitated through the solution resulting in breakdown of the gas, and in the heat-based systems, methyl bromide is trapped on carbon filter beds then heating to 400° F where decomposition begins (Swords, 2011).

  The USDA Animal and Plant Health Inspection Service, Plant Protection and Quarantine program (USDA APHIS PPQ) surveyed states to determine if facilities were utilizing methyl bromide recapture systems in 2020 and reported the results to USDA OPMP (USDA OPMP, 2020). Information was collected for seven facilities (spanning six states). Every facility used some type of capture system and most facilities utilized a carbon filtering system.

  In 2019, Nordiko International, a company that produces fumigant capture and ventilation systems, provided some recapture equipment purchase price estimates per type and size of container for methyl bromide (USDA OPMP, 2020). These are provided in Table 1.

Table 1. Purchase price information for methyl bromide recapture systems

Application	Size (Cubic Feet)	Price ($)
Shipping containers	Up to 3,000	80,000 – 90,000
Fixed Chambers	0 to 35,000	65,000 – 75,000
Fixed Chambers	35,000 – 100,000	90,000 – 110,000
Fixed Chambers	> 100,000	From 130,000

Source: Nordiko International (2020)

Operational costs are largely driven by the disposal of the used media (activated carbon), and replacement of new media. Nordiko International estimated that the cost of recapture increases a methyl bromide fumigation cost by an additional 25-50%. For example: if it cost $200 to fumigate a 20-foot shipping container with methyl bromide without recapture, it can cost an additional $50 - $100 more for recapture due to the amount of media used.

In 2015, EPA examined the cost of methyl bromide capture and destruction systems for country ham production facilities (dry cured pork products were an approved Critical Use Exemption at that time) (EPA, 2015). To do this, EPA collected information on the costs of methyl bromide capture and destruction using estimates from two firms' technologies. The analysis found that a recapture and scrubbing system would increase the annual cost of a large facility treating country ham by $150,000 - $250,000 depending on the type of technology used.[1] The increase in cost represents the initial investment in equipment and equipment installation, and the scrubbing agent and disposal for the first year. These estimates reflect the possibility that firms could make an investment in scrubbing technology, use it for one year, and then find that methyl bromide is unavailable the following year. The annual recurring cost of the scrubbing agent and disposal for one firm is estimated to be $40,000 and is unknown for the second firm (EPA, 2015).

BEAD does not know whether the costs of capture for methyl bromide reported by Nordiko International or if the costs of capture in country ham facilities are indicative of the cost of capture for other types of fumigants.

Role of Fumigants in Integrated Pest Management

Integrated pest management (IPM) of stored grains and other commodities and structures includes the following: prevention and sanitation, pest resistant storage facilities, effective temperature control, aeration and moisture regulation, rotation of stock, monitoring of pest populations, use of chemical protectants, and fumigation.

[1] Analysis assumptions were for a 165,000 cubic foot facility with multiple aging rooms and an indoor walkway; fumigated 4 times per year and an application rate of 1.5 lb/1,000 cubic feet, held for 24 hours, half loss time of 8.5 hours (at this application rate, 990 lbs of methyl bromide are needed to treated 165,000 cu ft facility).

IPM control in grain storage is primarily accomplished by cleaning empty bins (includes sanitizing bins through use of chemicals), aerating ducts (forced air movement via a fan), and by removing spilled grain and vegetation near the bins. Temperature extremes can also be used to prevent insects or mites from surviving or reproducing in grain (Waters, 1991; Mueller, 1998; Hopkins and Johnson, 2013). Again, such measures are preventative and suppressive of infestations but are not effective for disinfesting stored grain once an infestation has started.

Holcomb and McLean (2010) reported on an IPM approach in pet food processing plants and warehouses and the approach is applicable and recommended for other structures or spaces (e.g., Walter, 2006; Hopkins and Johnson, 2013, UKPSEP, 2016). Holcomb and McLean (2010) reported having success in controlling pests in these facilities for over five years. They ensure outside sanitation around plants and warehouses. They also try to reduce introducing pests by inspecting incoming ingredients and goods to ensure they are "clean;" maintaining screens at windows and doors; and placing lights so that insects are not attracted to openings. Microsanitation (e.g., removal of spilled flour, meal, dust; cleaning floors, walls, cracks and crevices) and limiting the access of pests to sensitive areas are stressed in Holcomb and McLean's (2010) presentation on IPM approaches for structures and spaces. During the presentation Holcomb stressed that companies need to hire a sanitation team to ensure that the facility and all equipment could be thoroughly cleaned every 30 days to break the life cycle of stored product pests (which is typically about 45 days) (Holcomb and McLean, 2010).

In addition to sanitation practices designed to prevent pest infestations, several broad-spectrum chemical insecticides such as pyrethroids (e.g., cyfluthrins, pyrethrins) and organophosphates (e.g., chlorpyrifos, DDVP, malathion) as well as more selective insecticides including *Bacillus thuringensis* and insect growth regulators (e.g., methoprene) are recommended (University of Arkansas Extension, 2020). Insecticides applied as surface treatments in empty grain bins or facilities are recommended to treat or protect commodities and structures from pests in storage (Hopkins and Johnson, 2013; University of Arkansas, 2020). Generally, fumigation is only needed for pest control in structures and spaces when these methods have failed or are impractical. Aluminum phosphide, magnesium phosphide, PPO, sulfuryl fluoride, and carbon dioxide are commonly recommended fumigants for use on stored commodities (Hopkins and Johnson, 2013) and/or empty grain bins (Noyes et al., 1995b). Carbon dioxide is prohibitively expensive and requires special equipment. However, carbon dioxide or nitrogen may be used or formulated with other fumigants such as phosphine or PPO which results in increased insect respiration and more rapid inhalation of the fumigant (Mueller, 1998). When applicable, fumigators may rotate fumigants (e.g., phosphine and sulfuryl fluoride) for insect control in grains, fruits, or structures to prevent or delay the development of resistance. Further, fumigants such as phosphine and sulfuryl may be rotated to target different pest life stages as well as different pests (e.g., insect eggs, rodents). As fumigants are often the last option for pest infestations, few alternative sterilization technologies are available for pest control in commodities and structures. Non-fumigant alternatives include heat, steam and irradiation. However, facilities may not be equipped with practical methods to deliver heat, steam to all stored commodities and the exposure to heat and moisture may negatively impact the quality (e.g., mouthfeel, texture, aromatics, clumping of spices) or may not fully eradicate the pest from the commodity (FDA, 2013; ASTA, 2017). Further, irradiation sterilization methods do not have market acceptance in the U.S.

Economically Significant Pests in Commodities and Structures

Fumigation, albeit the final option in pest management, can significantly reduce catastrophic consequences like rejection of an entire shipment due to pest contamination or incidental food contamination that have significant health implications if a contaminated product is ingested.

Economically significant pests may reduce or result in the loss of marketability for commodities or directly infest or attack structures. Commonly encountered pests of economic importance that can infest or directly attack structures include termites and other wood boring insects, bed bugs, cockroaches, and rodents. Fumigation of food (e.g., grains, fruits, nuts, meats, herbs and spices) and non-food (e.g., clothes and fabrics, rugs and carpeting, shoes) commodities are most often used to manage insects, such as moths (e.g., Angoumois grain moth, Indianmeal moth, webbing clothes moth, Mediterranean flour moth) and beetles (rice, granary, and maize weevils, lesser grain borer, cigarette beetle, red flour beetle) (Hopkins and Johnson, 2013; UKPSEP, 2016). In addition to insects, rodents as well as microbes such as bacteria (e.g., *Salmonella, Escherichia coli*), fungi (e.g., aflatoxins, *Botrytis* spp.), molds, and yeasts are also common pests infesting food and non-food commodities as they can be human health hazards. Further, the fumigation of commodities can prevent the introduction of invasive species which can wreak havoc on the environment when introduced to new areas. APHIS's Plant Protection Quarantine program is specifically designed to safeguard U.S. agriculture and natural resources from economically and environmentally significant pests. Accordingly, this program maintains a list of regulated quarantine plant pests under the authority of the Plant Protection Act and imported commodities are inspected for these pests (USDA APHIS, 2020). If any such pests are detected shipments can either be returned to the point of origin or treated for the pest/disease.

Not all pests pose an equal threat. Some pests can cause significant damage because they feed on or reproduce in food (Schoenherr and Rutledge, 1991). Others, including some arthropods pose little hazard to human health when consumed, in fact their consumption can be impossible to avoid when eating many fruits and vegetables. Pests can have implications on human health in a number of manners – they can modify commodities reducing the palatability or nutritional value of a product or they can function as vectors where they can maintain or transmit pathogens (toxins and allergens), viruses, bacteria (*Salmonella* is a commonly carried by a wide assortment of pests), etc. (Brenner, 1991). Pests that act as potential vectors include birds, cockroaches, flies, ants, mice, rats, beetles, moths and mites. Some come into contact with food because they derive all of their food, water and shelter from stored foods, or they may simply come into contact with stored foods or they may use storage structures to rest, nest or roost (Gorham, 1991).

Insects are bound to show up sooner or later and will be found in many conveyances so a food safety or commodity import policy that calls for rejection of any food or conveyance because an insect is present can be devastating to the food supply (Schoenherr and Rutledge, 1991). Close monitoring and pest identification of products and spaces is important for both prevention and for planning the appropriate and most economical recourse for any infestation. For example, rodents or birds may have entered a conveyance but the significance of the problem should be investigated to see if the pest is still present or if the conveyance was already contaminated by urine, hair, feathers or feces. If bird excrement comes into contact with food this sort of contamination can be significant because of the high incidence rate of *Salmonella* associated with such contact (Schoenherr and Rutledge, 1991).

Fumigant Use and Usage

BEAD utilized data from Kline and Company and a non-agricultural market research firm. These companies collect information on pesticide sales and usage including fumigants applied for the control of pests of stored grains and by professional pest control operators for bed bugs and termites. Additionally, BEAD utilized pesticide usage data from California. The state of California requires pesticide users to report agricultural pesticide usage, so data from the California Department of Pesticide Regulation (CDPR) are the most comprehensive data BEAD has available on fumigant usage.

Individual fumigants are often specialized for a specific pest spectrum (e.g., insects or microbes) and/or pest life stage (e.g., insect eggs or larvae/adults). Table 2 provides a cross section of each fumigant and commodity use site, with the primary target pest(s) listed at the intersection. The table also shows where there is some overlap in use patterns. For example, phosphine, sulfuryl fluoride and PPO all target insects in fruits and nuts; however, only PPO targets microbes such as *Salmonella* in nuts.

Table 2 is not an exhaustive list of all commodity and space fumigant uses; niche uses of fumigants may not be captured here. For example, chloropicrin, which is not listed in Table 2, is excluded because it is primarily a soil fumigant applied pre-plant in agricultural fields. However, chloropicrin has a niche use as a remedial wood treatment that would be considered a post-harvest commodity use. In the case of phosphine, it is also used in stored tobacco, but this use does not fall into the primary uses of commodity and structural fumigants categories captured in Table 2.

Table 2. Common Use Sites and Primary Target Pests for Commodity and Structural Fumigants[1]

Commodity and Structural Fumigants	Ethylene Oxide (EtO)	Inorganic Sulfites[2]	Methyl Bromide[3]	Phosphine	Sulfuryl Fluoride	Propylene Oxide (PPO)
Buildings					Insects	
Chambers and Railcars[4]				Insects	Insects	
Grain			Insects	Insects, rodents	Insects	
Fruits & Nuts	Microbes	Mold on grapes	Insects	Insects	Insects	Insects, microbes
Herbs and Spices	Microbes		Insects	Insects		Insects, microbes
Wood and Wood Packaging			Insects	Nematodes		

[1] Table excludes non-agricultural commodities and non-structural fumigant use sites. Other non-agricultural commodity use sites are mentioned in the fumigant specific sections for any fumigant that has non-agricultural commodity use sites. For example, EtO is also commonly used in the sterilization of medical equipment.
[2] Includes sulfur dioxide & sodium metabisulfite.
[3] Sites listed are per uses reported in Johnson et al., 2012. All uses listed in the table are Quarantine and Pre-Shipment Uses (QPS). QPS uses refer to those required by regulatory entities to ensure pest-free commodities (often to protect US and trading partners from transport of significant pests). Critical Use Exemption uses (uses subject to approval by the EPA) of methyl bromide are not listed in this table because currently there are no active CUE's. See methyl bromide section for more information on these uses.
[4] Includes empty rail structures and rail structures that contain commodities.

Table 3 reports commodity and space fumigant usage in California by active ingredient and use site for the period 2013-2017 (CDPR, 2020). Since much of the fruit and nut production for the U.S. occurs in California, fumigant use on these sites may be more representative of national pounds applied than use on rice, other commodities, structural and other sites.

Table 3. Average Annual Usage of Commodity and Structural Fumigants in Pounds Active Ingredient in California (2013-2017)

Active ingredient[1]	Total Pounds Active Ingredient	Nuts	Fruits (Except Grapes)	Grapes	Rice	All Other Commodities[2]	Structural	Other[3]
Sulfur Dioxide	**253,100**	-	-	152,500	-	-	-	100,600
Sodium Metabisulfite	**5,200**	-	-	5,200	-	-	-	-
Inorganic Sulfites Total	**258,300**	**-**	**-**	**157,700**	**-**	**-**	**-**	**100,600**
Methyl Bromide[4]	**255,400**	**21,300**	**22,000**	**-**	**100**	**86,200**	**200**	**123,300**
Phosphine	**19,900**	6,900	600	-	500	6,700	-	5,200
Phosphide, Al	**160,600**	50,200	13,200	3,000	19,600	22,200	14,900	37,500
Phosphide, Mg	**13,200**	6,700	200	-	-	2,700	300	3,000
Phosphides Total	**193,700**	**63,800**	**14,000**	**3,000**	**20,100**	**31,600**	**15,200**	**45,700**
Sulfuryl Fluoride	**3,171,500**	**134,200**	**11,800**	**-**	**11,000**	**311,900**	**2,698,500[5]**	**4,100**
Propylene Oxide	**366,200**	**115,300**	**-**	**-**	**-**	**230,100**	**-**	**20,900**

Source: CDPR, 2020. "-" indicates no usage reported.

[1] Ethylene Oxide (EtO) not listed in the table because it is primarily used for spices and medical device cleaning and CDPR does not capture these uses. See EtO section, "Benefits and impacts if not available" for information on EtO usage.

[2] Commodities include raw agricultural products like grains, cotton and beans. This category includes all other commodities besides those already specified in the table (rice, nuts, fruits).

[3] "Other" column represents where CDPR categorized as "fumigation, other," "regulatory pest control," or other uses of the fumigant that could not easily be categorized. Also includes use sites BEAD could not interpret because reported use site was not an expected use pattern for the respective fumigant.

[4] Excludes soil fumigation uses. Commodity (nuts, fruits, rice, etc.) applications of methyl bromide are for quarantine.

[5] The bulk of sulfuryl fluoride structural applications target termites; some use may be for stored-product pests, bed bugs, cockroaches and other indoor pests.

Table 4 summarizes national level usage data aggregated from Stored Grain Insect Control and Professional Pest Management Market reports made available by Kline and Company[2] and a non-agricultural market research firm.

The Stored Grain Insect Control reports are based on survey data collected on pesticides sales and use to control insects and rodents in stored grain. The survey collects information for sales and use of on-farm, off-farm, and export grain treatments and provides a summary of pest treated by commodity. The Professional Pest Management Market reports provide information on the use of pesticides by professional pest management companies, including their control practices, demographics, and sales and market share by pest type, product, active ingredient, and company.

Table 4. Average National Annual Usage of Commodity and Structural Fumigants.

Active Ingredient	Total (lbs. ai)	Commodities		Structural
		Stored Grain Except Rice (lbs. ai)[1]	Rice (lbs. ai)	Termites and Bed Bugs (lbs. ai)[2]
Phosphine	60,000	60,000	-	-
Phosphide, Al	1,100,000	1,067,000	43,000	-
Phosphides Total	**1,160,000**	**1,127,000**	**43,000**	**-**
Sulfuryl Fluoride	**2,000,000**	**490,000**	**10,000**	**1,500,000**
Methyl Bromide	**10,000**	**10,000**	**-**	**-**

Source: Stored Grain Insect Control from Kline and Company, 2012; Kline and Company, 2016; Non-agricultural Market Research Data, 2018.

[1] Stored Grain use from Kline and Company, 2012; Kline and Company, 2016; Non-agricultural Market Research Data, 2018. Annual averages for stored grain based on 2011, 2015 and 2017 data. 75% of use is reportedly used on drywood termites with the remaining use on subterranean termites and bed bugs.

[2] Termite and bed bug use from Non-agricultural Market Research Data, 2017; Kline and Company, 2013.Annual averages for termite and bed bug use based on 2012 and 2016 data. 75% of use is reportedly used on drywood termites with the remaining use on subterranean termites and bed bugs.

PHOSPHINE

Phosphine gas is colorless and is effective against stored-product insect pests and vertebrate pests, mainly rodents. Aluminum phosphide and magnesium phosphide liberate phosphine gas when exposed to atmospheric moisture. Unless noted below, phosphine will refer to all three chemicals. While the complete mode of action of phosphine is unknown, the Insecticide

[2] Kline and Company is a consulting and market research company that surveys and produces studies on select industries. One of their specialties is in surveying companies in the nonagricultural pesticide market in the United States and reporting those results. The EPA has access to select reports from Kline & Company including reports on stored grain insect control use in the calendar years 2011 and 2015, and reports on professional pest management markets use for the calendar years 2012 and 2016.

Resistance Action Committee (IRAC) has classified phosphine as a Group 24a mitochondrial complex IV electron transport inhibitor. There is some evidence that phosphine exposure also decreases acetylcholine esterase activity as well as increasing oxidative stress in cells (Nath et al., 2011).

Relative to other fumigants, phosphine gas is liberated slowly and thus requires a longer fumigation time period (as much as two, and in some cases three days) in order to kill all life stages of insects (Walter, 1991). While a prolonged exposure period may make phosphine an impractical fumigant in certain scenarios, the ability of phosphine to be used for in-transit fumigations of commodities over several days on railcars or in ship holds is advantageous. An inadequate exposure period allows for pest survival and as a result there are many reports that cite the development of insect resistance to phosphine (Fumigants and Pheromones, 2012; Phillips and Opit, 2013). Therefore, integrated pest management programs for stored bulk grain are cited as important to implement to ensure long-term viability of phosphine. Another consideration important when considering phosphine as a pest management option is temperature control. Temperatures must be above a certain point for phosphine to be effective but at too high of temperatures and humidity it can corrode copper, gold and silver (Schoenherr and Rutledge, 1991; Walter, 2006).

Use Sites and Target Pests

Phosphine is an insecticide/rodenticide labeled for use on numerous stored raw commodities (i.e. tress nuts, dried fruits, cereal grains, tobacco), animal feed and feed ingredients, and processed foods (i.e. candy, bakery mixes, crackers, cheese, meat products).

Phosphine is also labeled for use on numerous non-food commodities and other non-food items. These include tobacco, cloth fibers, feathers, hair, wood and wood products, paper, tires, and beehives.

Phosphine gas is effective against stored-product insect pests (all life stages) and vertebrate pests, mainly rodents. Some pests that are controlled by phosphine are Africanized honeybees and diseased bees, moths (e.g., almond moths, Angoumois grain moths, dried fruit moths, greater wax moths, Indianmeal moths, Mediterranean flour moth, tobacco moths), beetles (a variety of grain, fruit, and tobacco beetles), flies (e.g., fruit flies, hessian flies), and mites.

Aluminum and magnesium phosphide products also can be used to control rodents (e.g., gophers, marmots, mice and rats, moles and voles, prairie dogs, squirrels). Some rodents may carry and transmit various diseases including Sylvatic plague (bubonic or pneumonic plague in humans). In cases where the purpose of treatment is to control for a vector-borne disease the use would be considered a public health use. Pellets or tablets are placed into the rodent burrows. However, these products may not be used in burrows that are within 100 feet of a building that is, or may be, occupied by humans and/or domestic animals.

Facility Types and Application Methods

Phosphine may be applied as a structural or space fumigation (under tarps, mills, food plants, warehouses); as a vehicle fumigation (railcars, trucks, vans, containers); as a commodity fumigation (raw agricultural, processed foods); as a grain fumigation (silos, farm storage, flat storage); and as a vessel or ship fumigation.

Formulations

Phosphine is formulated as a pressurized gas. Aluminum and magnesium phosphide are also formulated as prepackaged impregnated or gas permeable materials (e.g., bags, plates) as well as pellets, tablets, and strips which are standardized to release a specific amount phosphine gas upon exposure to atmospheric moisture. Product formulations such as pellets and tablets can be placed directly into a commodity or space or inserted inside cylinder tubes/probes that are then placed into the commodity or space (Hopkins and Johnson, 2013).

Key Benefit

Phosphine and the metal phosphides play a vital role in controlling pests that infest structures or spaces that store commodities. Pests controlled by phosphine have public health and economic importance and include both stored-product insect and vertebrate (rodent) pests. These pests can spread diseases in humans (e.g., rodents and Sylvatic plague) and/or result in the adulteration or spoiling of food and non-food commodities (e.g., tobacco) that are in storage or transit. While the exposure times for structures or spaces with goods fumigated with phosphine are generally prolonged relative to other fumigants, a key advantage is that phosphine is effective against all insect life stages and provides flexibility to fumigators who may utilize in-transit commodity (e.g., grains) fumigations that may take place over several days on railcars or in ship holds. Moreover, products such as pellets, tablets, or other prepackaged options are standardized to release a certain amount of phosphine gas, making them easy to use in spaces with known volumes or as spot treatments to disinfest machinery or food processing equipment (Hopkins and Johnson, 2013).

PROPYLENE OXIDE (PPO)

PPO is an epoxide compound that exists at room temperature as a volatile colorless liquid (NTP, 2011). PPO has conventional and antimicrobial uses. PPO may be used as an insecticide as well as a microbicide for the sterilization of packaged foods and commodities against both public health and non-public health pathogens.

Use Sites and Target Pests

PPO is used on food items such as dried herbs and spices, dried onions, dried garlic, cacao beans, cocoa powder and in-shell and processed nutmeats (except peanuts), dried fruits such as figs, plums (prunes), and raisins. PPO is also used for the sterilization of pharmaceutical materials.

PPO is an insecticidal fumigant and sterilant used to control insects as well as bacterial (e.g., *Salmonella)*, fungal (e.g., aflatoxins), and mold contamination and to ensure food safety and prevent microbial spoilage of food and non-food products. PPO is widely used to treat nutmeats (except peanuts) and spices for the reduction of *Salmonella*, aflatoxins, and other pathogens. Applications of PPO for reducing levels of *Salmonella* and aflatoxins are considered public health uses.

Facility Types and Application Methods

As noted on the PPO labels, 100% pressurized gas product may only be used in vacuum-sealed pressurized chambers. Such chambers may be up to 10,000 ft^3 in size.

When used in combination with carbon dioxide or nitrogen, PPO may be used in various settings such as atmospheric and vacuum chambers, tarpaulin, stationary railcars and trailers, storage containers, empty process facilities or other enclosed structures where gas may be confined, and entrance restricted during fumigation. The maximum size enclosure that is permitted to be fumigated, according to label requirements, with this product is 100,000 ft^3.

Formulations

PPO can be formulated as a pressurized liquid or a pressurized gas. It is used in vacuum chambers at full strength (100%) for nuts, spices, cocoa (cacao) bean, cocoa powder, and cosmetics. It must be used at a concentration of 8% with an inert gas (carbon dioxide, nitrogen) for figs, dried plums (prunes), and raisins.

Key Benefit

Postharvest fumigations with PPO are widely used and beneficial for stored commodities and packaged foods because they can be used to disinfest the product from insects or microbes, which is critical to prevent food spoilage in addition to ensuring food safety for human consumption. Commodities that may be commonly fumigated with PPO include processed nutmeats (except peanuts), dried herbs and spices, dried fruits (e.g., figs, plums, raisins), cocoa (cacao) bean, cocoa powder, and cosmetics. PPO is important for the nut, herb and spice industries for reducing the levels of public health and non-public health bacteria and fungi such as *Salmonella*, aflatoxins, and other pathogens present in raw nuts and herbs and spices intended for human consumption (ABC, 2012; Elite Spice, 2012; FDA, 2013; ASTA, 2017).

INORGANIC SULFITES: SULFUR DIOXIDE AND SODIUM METABISULFITE

Sulfur dioxide is an inorganic pesticide with multisite mode of action against microorganisms which the Fungicide Resistance Action Committee (FRAC) has classified as group code M2 fungicide (FRAC, 2020). Further, FRAC considers there to be a low risk of microorganisms developing resistance to sulfur dioxide. Sulfur dioxide can also be used as an acaricide.

Sodium metabisulfite is an inorganic sulfite which releases sulfur dioxide. Sodium metabisulfite is used as a fungicide to target fruit rot, gray mold and other *Botrytis* diseases on grapes as a post-harvest or storage area treatment. Additionally, sodium metabisulfite has an antimicrobial registration for the prevention of microbes on consumer goods for use in storage and shipment containers.

Use Sites and Target Pests

Sulfur dioxide is registered for post-harvest fumigation of grapes. It is also registered for sanitation of barrels and corks in the wine industry. Sulfur dioxide has antifungal and antimicrobial properties and is used for the control of gray mold (also called bunch rot) caused by *Botrytis cinerea* on grapes during storage and transport. Sulfur dioxide is also used in the wine industry for the sanitation of wine corks and barrels from non-public health microbes. It also has a niche use for treatment of black widow spiders in grapes for export markets.

Sodium metabisulfite is used as a postharvest or storage area treatment for grapes to treat *Botrytis cinerea*, which causes gray mold and other *Botrytis* diseases on grapes. Gray mold is one of the most destructive postharvest diseases of grapes because it continues to grow after grapes are harvested. No biological control is available and cold storage, a cultural control, can only slow the disease development (UCANR, 1999). During the preharvest phase, "botrytis infection can be reduced by removing desiccated, infected grapes of the previous season from vines, leaf-removal canopy management, preharvest fungicides, trimming visibly infected, split, cracked, or otherwise damaged grapes before packing, [and] prompt cooling..." (Crisosto et al., 2009).

Sodium metabisulfite is also used as an antimicrobial in the storage and shipment of consumer goods such as shoes, purses, clothing, and other merchandise to. prevent odor-causing bacteria, mold, and mildew.

Facility Types and Application Methods

Sulfur dioxide is used for grapes held in cold storage, fumigation of trailers, railcars, and other transportation vehicles, and warehouses as well as for the sanitation of barrels and cork in the wine industry.

Semi-sealed pads or bags impregnated with sodium metabisulfite (rates vary from 8.6-98.5% active ingredient) are placed inside storage and shipment containers of fresh grapes. The pads slowly release sulfur dioxide up to 1-5 ppm within the containers as they absorb moisture.

Formulations

Products containing sulfur dioxide as the active ingredient are formulated as liquid and sold in pressurized containers. These products contain 99.9 - 100% sulfur dioxide and turn into gas upon release of pressure. Sodium metabisulfite products are composed of the anhydrous, solid active ingredient contained in semi-sealed pads (or liners) that release sulfur dioxide, which is toxic to microbes such as fungi, when mixed with water or exposed to moisture. These products are placed in containers holding grapes or consumer goods for shipping and storage.

Key Benefit

Sulfur dioxide and sodium metabisulfite are mainly used for controlling gray mold fungal growth caused by *Botrytis* spp. on grapes in storage. Gray mold is one of the most destructive postharvest diseases of grapes because it continues to grow after grapes are harvested and causes grape berries to become soft and watery or brown and shriveled. Damage from gray mold can result in complete crop loss or marketability. There are no alternative postharvest chemical or biological control options to the inorganic sulfites for gray mold control on grapes. Cold storage (without sulfur dioxide), a cultural control, can only slow the development of gray mold. Therefore, sulfur dioxide and sodium metabisulfite have high benefits in grapes. Further, sulfur dioxide is important for international trade as it is used for quarantine purposes to prevent the movement/introduction of black widow spiders in grapes to certain export markets. Additionally, sulfur dioxide and sodium metabisulfite provide benefits from the sterilization of wine barrels and corks and consumer goods (e.g., purses, shoes) from non-public health microbes.

SULFURYL FLUORIDE

Sulfuryl fluoride is a biocide fumigant that is used to kill insect pests, rodents, birds, and snakes within facilities as well as commodities. Sulfuryl fluoride was initially registered as a fumigant to treat drywood termites and other wood boring insects. It is now also registered for food processing facilities, cereal grains, tree nuts, and dried fruit, and is considered a post-harvest alternative for methyl bromide. Sulfuryl fluoride is non-flammable and non-corrosive.

Use Sites and Target Pests

Sulfuryl fluoride is registered both for direct fumigation of certain commodities (e.g., rice) and for fumigation of grain mills and food processing plants where food may be present and may be indirectly treated. Food processing plants are cleaned before fumigation, but it may not be feasible to remove all grains and mix ingredients from the facility prior to treatment. In addition to use in grain mills and food processing plants, sulfuryl fluoride is the most widely used fumigant for structural pest fumigations in buildings and homes (Kline & Company, 2012; Kline & Company, 2016; Non-agricultural Market Research Data, 2018; CDPR, 2020). Additional use sites include vehicles (e.g., stationary cars, railcars, buses, or trucks).

Sulfuryl fluoride controls insect pests, including termites, cockroaches, and bed bugs as well as rodents, birds, and snakes in structures/facilities and commodities. While sulfuryl fluoride can kill insect eggs in stored products, it is reported to be more effective against post-embryonic life stages (Johnson et al., 2012).

Formulations and Application Methods

Sulfuryl fluoride is stored in standardized, compressed gas containers, which are placed outside the structure and the gas is introduced from the cylinder through a leak-proof tube. The label for sulfuryl fluoride requires the use of electric fans to provide forced air circulation for facilitating rapid dispersion of the fumigant during its introduction into spaces or air recirculation through commodity fumigation.

Sulfuryl fluoride's label requires the use of a computer program (Fumiguide) during the fumigation process. The Fumiguide is useful for fumigators as the program calculates the application rate based on the pest's life stage, temperature, wind speed, volume of the structure, and exposure period for specific fumigation scenarios. Because the Fumiguide is part of the pesticide label, it is unlawful under FIFRA to use sulfuryl fluoride in a manner inconsistent with the Fumiguide. Monitoring concentrations throughout the fumigation is required and concentrations are input into the Fumiguide, which will calculate the actual half-life time and any additional amount of fumigant and/or increase in exposure time necessary. In addition, sulfuryl fluoride fumigations require a minimum of two trained and certified applicators, at least one of whom must be a licensed fumigator, at the treatment site for the duration of the application and aeration. Licensed fumigators may work at large grain storage facilities, but typically, work for fumigation companies.

Key Benefit

Sulfuryl fluoride controls a wide range of pests in commodity and space fumigations. In commodities, sulfuryl fluoride can be used against phosphine resistant pests (Fumigants and Pheromones, 2012). As sulfuryl fluoride is non-flammable and non-corrosive it is often the top choice for fumigating buildings and structures. Sulfuryl fluoride is highly effective for the control of structural pests such as drywood termites, bed bugs, cockroaches, wood boring insects, and rodents that infest buildings and homes. It offers a quick kill of the target pest in a short fumigation time and attains excellent penetration of the fumigated product. Fumigation times are shorter than phosphine or metalized phosphine. The concentration of the gas can be accurately monitored and controlled using the Fumiguide.

ETHYLENE OXIDE (ETO)

EtO is a fumigant, sterilant, disinfectant and insecticide. EtO has conventional and antimicrobial uses. EtO is used as a microbicide for pathogen control (e.g., *Salmonella* and *Escherichia coli*) in herbs spices in addition to uses for the sterilization of medical equipment/devices.

Use Sites and Target Pests

EtO is registered for herbs and spices in addition to processed vegetables (dried/dehydrated). EtO is also registered for medical device/equipment sterilization and the preservation of archival and museum materials, musical instruments, and certain ingredients in cosmetics.

The threat of food-borne contamination and the potential for serious illness is a concern for the Agency, food manufacturers, and the general public. EtO is used in the U.S. during the processing of spices to reduce microbial activity. EtO is currently used to treat certain spices that may lose desired characteristics (e.g., aromatics) or result in clumping if treated with one of the main alternatives, heat/steam. However, even for spices where heat or steam are not an appropriate treatment, other methods (e.g., PPO or irradiation of spices outside of the U.S.) enable selection and processing of spices that provide consumers with safe and quality products.

The American Spice Trade Association (ASTA) reports that the spice industry uses approximately 800,000 lbs of EtO on an annual basis which represents less than 10% of all EtO usage in the U.S. (ASTA, 2017). Most EtO usage in the U.S. is for sterilization of medical equipment (ASTA, 2017).

The EPA Office of Air Quality Planning and Standards collected and performed an internal analysis of allowable (i.e., the maximum amount a facility is allowed to use over the span of one year) and actual (i.e., the amount the facility used over the span of one year) usage of EtO in sterilization facilities throughout the U.S. and Puerto Rico from various sources. These facilities encompass all commercial sterilization facilities (i.e., medical device, spice, and other uses for sterilization), but do not include smaller scale activities such as hospital sterilizers. Overall, from 2015-2019, allowable use across all commercial EtO sterilization facilities is about 1,800 tons per year (EPA, 2020b). The actual use from these sterilization facilities represents about 55% of the allowable use (about 1,000 tons annually) in these facilities (EPA, 2020b). These data omit usage from facilities that did not provide allowable use or typical use data or dates, and therefore, may be an underestimation of EtO usage in the U.S.

Facility Types and Application Methods

Per the EtO product label, sterilization or fumigation with EtO must be performed in vacuum or gas tight chambers with outside venting designed for use with EtO. EtO is shipped in compressed gas cylinders and is fed into the fumigation chamber by means of tubing.

Formulations

EtO is formulated as a pressurized gas. When EtO is used for the sterilization of medical equipment/devices in some use sites (i.e., hospitals and healthcare facilities), EtO must be used alone; however, EtO may be mixed with an inert gas (i.e., carbon dioxide) for other uses.

Key Benefit

Salmonella and *Escherichia coli* are the primary food safety concerns for the spice industry (Elite Spice, 2012; FDA, 2013; ASTA, 2017) and EtO is highly effective in eliminating or reducing the levels of these potential health hazards. EtO is simultaneously effective against non-food safety related microbiological specifications including spoilage due to bacteria, yeasts, and molds. According to a 2017 publication by the American Spice Trade Association (ASTA), current FDA standards require proof that certain specifications (i.e., removal of contaminants such as pathogenic microbes, overall bacterial load including coliforms, mold, yeast) are met in spices and EtO is able to meet these specifications at no sacrifice to product quality. ASTA (2017) also reported that current alternatives including heat and irradiation require additional research to prove that FDA standards can be met without sacrificing the quality of the product.

METHYL BROMIDE

Methyl bromide is a broad-spectrum fumigant chemical that can be used as an acaricide, antimicrobial, fungicide, herbicide, insecticide, nematicide, and vertebrate control agent for soil fumigation uses and for fumigation of imported and domestic commodities. Methyl bromide's use on quarantine pests found in soil is discussed in Chism and Sells (2019).

Because methyl bromide is an ozone depleting substance its production is controlled under the Montreal Protocol on Substances that Deplete the Ozone Layer (Protocol) and the Clean Air Act (CAA). Most methyl bromide uses were phased out through a process which was completed on January 1, 2005 (EPA, 2020c); the only remaining uses of methyl bromide are those for which there are no other technically or economically feasible alternatives available. These uses include Quarantine and Pre-shipment Uses (QPS's) and Critical Use Exemptions (CUE's). QPS uses refer to those required by regulatory entities to ensure pest-free commodities. These uses are often to protect U.S. and trading partners from transport of economically and environmentally significant pests.

CUE's are subject to EPA approval and granted through an application process by which an entity must prove to the EPA that (i) the specific use is critical because the lack of availability of methyl bromide for that use would result in a significant market disruption; and (ii) there are no technically and economically feasible alternatives or substitutes available to the user that are acceptable from the standpoint of environment and health and are suitable to the crops and circumstances of the nomination. The last CUEs were approved in 2016 (EPA, 2015) and there are currently there are no active CUEs. Since 1994, there has been a collective research effort to develop and implement economically viable and environmentally sound alternatives for methyl bromide through the Methyl Bromide Alternatives Outreach forum (MBAO, 2020). On an annual basis, researchers from governmental, academic and private institutions, as well as extension agents and users come together for a conference to share information on issues related to identifying alternatives to methyl bromide for pre-plant, post-harvest and structural uses.

These ongoing research efforts illustrate that there is no easy or simple solution to replacing methyl bromide.

Use Sites and Target Pests

Methyl bromide is registered for QPS fumigation. Approved use sites include structures (e.g., flour mills, rice mills), post-harvest treatment of food commodities (e.g., tree fruit, tree nuts, berries, grains, vegetables, cocoa, dried fruits, cheese, processed grains, and processed herbs and spices), and post-harvest treatment of non-food commodities (e.g., logs, tobacco, cotton machinery). Methyl bromide is also used for structural and industrial fumigation treatments of large food handling and non-food handling establishments (e.g., warehouses, grain elevators, ships, food processing plants, etc.). In addition to QPS uses, stocks of methyl bromide may be used for the control of *Tyrophagus putrescentiae* or ham mites on country ham as dry cured pork products were determined to be a critical use (EPA, 2015). Severe ham mite infestations result in the meat having a putrid smell as well as the accumulation of brown dust on the surface and crack and crevices of the ham (Zhang et al., 2018). There is no single effective alternative to methyl bromide for the control of ham mites and infestations result in product rejection and economic losses (Zhang et al., 2018).

Facility Types and Application Methods

Treatments often occur in fumigation chambers, as well as structural/space fumigation of commercial shipping containers, storage and warehouse premises, and transportation facilities. It should be injected into a structure through plastic tubes or steel or copper pipes for safety purposes; in the absence of oxygen, it can be explosive when in contact with aluminum and magnesium pipes (Walter, 1991).

Formulations

Methyl bromide is commonly formulated as pressurized gas and applied as a gas for food and nonfood commodity fumigation treatments.

Key Benefit

Methyl bromide is beneficial because it is highly effective on a variety of pests (and pest life stages) in many situations, and because it requires only a short treatment period which makes this chemical highly desirable particularly at port facilities where shipping or port logistics require relatively quick throughput in addition to international trade standards that require phytosanitary certification (Johnson et al., 2012; FAO, Secretariat of the International Plant Protection Convention, 2016; Yang et al., 2015). Such characteristics have made transitioning away from methyl bromide in some postharvest (i.e., dry cured pork products) and QPS scenarios difficult. Alternative fumigants may not be able to provide the fumigators with the same combination of short treatment time (e.g., phosphine) and efficacy. For example, while sulfuryl fluoride is very effective against post-embryonic life stages of insect pests it is not nearly as effective as methyl bromide for controlling insect eggs (Johnson et al., 2012).

The use of methyl bromide on dry cured ham products as well as for QPS purposes are considered highly beneficial because if pests are present the product may not be sold or would be sold at a severely reduced price. If methyl bromide were not available other chemical or physical treatments, if feasible, would have to be used. However, these alternatives are unlikely to match the highly coveted characteristics of methyl bromide. A pest manager would have to consider how to balance the increased cost, longer fumigation time periods or reduced effectiveness of an any potential alternative.

CONCLUSION

Fumigants used on commodities and structures storing commodities are beneficial because they control economically important pests, including those which are critical to control to ensure food is safe for human consumption as well as pests whose damage may result in the adulteration or spoilage of food and non-food commodities. Further, fumigants provide benefits to users as they can be used to control pests that directly attack or infest structures (e.g., termites, bed bugs). This document summarized the key benefits of commodity and structural (or space) fumigants and provided information on how these fumigants are deployed in order to inform viable risk mitigation proposals for these types of fumigants.

Advantages of fumigants include: 1) pest control options that are fast acting and/or broad-spectrum that may result in pest eradication, 2) the ability to penetrate and treat commodities and structures that cannot be easily reached with other pesticides while leaving minimal or no surface residues, and 3) the combined suite of commodity and space fumigants offer multiple methods of application, and this in turn allows fumigants to be applied to many different pests and use sites. Fumigants are also important in preventing the movement of pests from one location to another which facilitates safe international trade and protects U.S. agriculture and natural resources from the entry, establishment and spread of an economically or environmentally significant pest.

The fumigants covered in this document along with the key benefit of each is summarized here:

- Phosphine and metal phosphides (aluminum and magnesium phosphide) offer broad-spectrum pest control of insects (all life stages) and rodents. Phosphine is widely used for the protection of grains and other commodities and can be used to fumigate in-transit commodities in railcars and ship holds.
- Propylene oxide (PPO) is used on a wide variety of commodities to control insect pests and microbes to ensure food safety for human consumption. PPO can control *Salmonella,* aflatoxins, or other pathogens on raw nuts as well as herbs and spices.
- Inorganic sulfites (sulfur dioxide, sodium metabisulfite) are critical for the protection of grapes from gray mold. Without the control of gray mold on grapes in storage or transport, complete loss may occur as the grapes quickly rot and become unmarketable.
- Sulfuryl fluoride is highly important for the control of pests such as drywood termites, wood boring insects, bed bugs, and cockroaches in structures and buildings. Sulfuryl

fluoride is also valuable for protecting commodities such as grain and may be used against phosphine resistant pests.

- EtO is important for ensuring food safety from the control of pathogens such as *Salmonella* and *Escherichia coli* on herbs and spices. It is also commonly used in medical device sterilization.
- Methyl bromide is effective against many pests in a wide variety of commodities, requires a short exposure period for efficacy, and easily diffuses and rapidly penetrates the pore spaces of commodities. Although most uses have been phased out, methyl bromide remains highly coveted for trade purposes. Its fast-acting and highly efficacious characteristics make it ideal at port and inspection sites where treatments are time sensitive and international phytosanitary standards require that certain pests be killed at very high rates.

Without effective fumigants users might have to shut down a facility and use micro-sanitation to clean and sanitize the structure, destroy contaminated product, or sell it at a substantially reduced price. Destroying contaminated product can be exorbitantly expensive and reduce the food supply.

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